Supplementary Material: Atlantic Meridional Overturning Circulation: Observed transports and variability

1 SUPPLEMENTARY DATA

Additional efforts to make time series observations of Atlantic meridional transports are outlined here. This are distinguished from observational programs outlined in the main body of the paper in that these do not (or have not yet) produced estimates of the AMOC and instead focus primarily on a particular component of the AMOC at a given latitude, e.g. the Deep Western Boundary Current (DWBC).

1.1 The "53°N Array" (Western Boundary Array)

Off the coast of Labrador the DWBC carries water masses of the North Atlantic Deep Water (NADW) southward: Denmark Strait Overflow Water (DSOW), Iceland Scotland Overflow Water (ISOW), and the Labrador Sea Water (LSW). Here the 53°N Array has been installed since 1997 to directly observe the DWBC flow and its properties. In the following, a brief overview about the methodology and the most recent results from the 53°N Array are presented while detailed information can be found in Zantopp et al. (2017).

Methodology: The 53°N Array is an array of moorings installed at the continental margin off Labrador in water depths from about 1500 to 3600 m. The number of moorings is typically 6 to 7 but in the past, due to funding limitations and mooring failures, there were periods with data only available from 1 to 3 moorings. Ideal sampling of the DWBC is determined by combining ship observations carried out along the array and moored observations. Velocity is measured with single-point rotor and acoustic current meters and occasionally with acoustic Doppler current profilers (ADCPs). In the full array configuration, four moorings recover data from close to the surface to the sea floor while in between, short moorings are installed to monitor the movement of the core of the Lower North Atlantic Deep Water (LNADW; comprising ISOW and DSOW). In the deep water the array is terminated by one short mooring to capture signals from the counter-flow of the DWBC.

Results: Volume transport for the NADW is 30.2 ± 6.6 Sv, which is almost equally partitioned between LSW (14.9 ± 3.9 Sv) and LNADW (15.3 ± 3.8 Sv). Transport variability ranges from days to decades, with the most prominent multi-year fluctuations at interannual to near-decadal time scales (± 5 Sv) in the LNADW overflow water mass. The LSW layer does vary, but not in correlation with deep convection intensity in the Labrador Sea. Long-term fluctuations in the LNADW appear to be in phase with the NAO-modulated wind fluctuations. The boundary current system shows a weakly sheared LSW range, and a baroclinic bottom-intensified current core for the LNADW. This structure is relatively stable over time. The counter-flow reduces the transport by 10–15%.

1.2 47°N and North Atlantic Current

In the subpolar and northern North Atlantic, the circulation and transport variability of the North Atlantic Current (NAC) are instrumental in setting the meridional heat and salt transport in the North Atlantic and in consequence strongly influences the mean state and the variability of the climate, especially in Western Europe (e.g., Palter, 2015). Under global warming, both the AMOC and NAC are expected to weaken in the next decades, leading to a reduction in the projected temperature rise in Western Europe (IPCC, 2013). The DWBC transports NADW components from the formation regions in the northern North Atlantic to the south, thereby advecting climate signals introduced during formation of these water masses into the southern hemisphere (e.g., Fine et al., 2002; Rhein et al., 2015). Variability in the deep water formation also influences the AMOC in the subtropical Atlantic (e.g., Jackson et al., 2016).

Methodology. The NOAC array consists of conventional moorings (temperature and salinity sensors, and acoustic current meters) in the boundary currents and Pressure-equipped Inverted Echo Sounders (PIES) along 47°N and the western flank of the Mid-Atlantic Ridge (MAR) from 47°N to 53°N. The deployment along the MAR started in 2006 and is on-going. Because of the importance of 47°N as a choke point for the inflow of subtropical water into the subpolar gyre (Mertens et al., 2014), five PIES were deployed in later years between 42°W and 37°W to resolve the northbound and the southbound pathways of the NAC. The deployment in the eastern basin (two PIES and two boundary current moorings) started in 2016. On some of the moorings, upward looking 75 kHz ADCPs monitor the velocity profiles. PIES data are combined with Argo profiles and shipboard hydrography to calculate the geostrophic transport employing the Gravest Empirical Mode (GEM) technique. Briefly, this method uses historical CTD and Argo data, and the travel times of the acoustic signals, emitted every 30 minutes from the PIES transducers at the ocean bottom to the surface and back to determine a geopotential anomaly profile at each PIES site. The geostrophic velocity profile is calculated between two sites relative to a common reference level. Each PIES is subject to an unknown individual drift of pressure sensors which prevents the calculation of the absolute velocity at the reference level, so bottom pressure variations only are used to calculate barotropic velocity variations at the chosen reference level.

Along the MAR, a reference level of 3400 dbar is well below the sill depth of the MAR, and the mean velocity at that level is assumed to be zero. At 47°N, a level of no motion does not exist, and the absolute surface velocities from the mean dynamic topography are inferred from altimetry (MADT) provided by AVISO and now CMEMS. In general, these velocities correlate well with the shipboard ADCP velocities. To expand the transport time series, the significant relationship between the PIES data and altimetry is applied (Rhein et al., 2011; Roessler et al., 2015), so that a time series from 1993 to January 2018 is available. To obtain an estimate of the AMOC at 47°N, the western and the eastern transport time series will be combined. The first analysis of the eastern PIES shows a high correlation with the altimeter signals.

Results. Roessler et al. (2015) used the PIES observations along the MAR from the time period 2006–2010 to carry out a regression with the altimeter-derived surface velocities. The updated NAC transport time series (time period 1993–2018) following Roessler et al. (2015) shows a mean transport of 30.1±0.6 Sv, similar to the PIES-only estimate (time period 2006–2016) of 29.6±0.3 Sv. Taking only the eight repeat lowered ADCP (LADCP) sections since 2006 gives a mean transport of 30.9±4.8 Sv. Positive and negative deviations between the LADCP-based absolute transport and the PIES/altimeter-based transport relative to 3400 dbar, and the fact that the mean transports agree within uncertainties, substantiate the assumption of a near zero velocity at the reference level as applied in Roessler et al. (2015).

The NAC transports at the MAR are only a fraction of the transports reported at 38°N and 42°N, but resemble the estimates from the Florida Straits. The transition seems to occur around 47°N. Five hydrographic repeats including LADCP measurements at 47°N carried out between 2003 and 2011, the results from the moorings in the boundary current and the results from the eddy-resolving 1/20° VIKING ocean model (Mertens et al., 2014; Breckenfelder et al., 2017) point to three permanent circulation features, located between 44°W and 38°W. Directly at the continental margin, the DWBC flows southward. Just east of the DWBC, the northward flowing NAC is observed, hugged in the east by a strong southward return flow, dubbed the Newfoundland basin recirculation (NBR, Mertens et al., 2014). A manuscript about the continuous transport time series of the main flow features in the western basin at 47°N calculated from PIES and altimetry is in preparation.

1.3 TSAA 11°S (Western boundary array + AMOC)

At the equator, transport variability is associated both with the meridional transfer of warm and cold watermasses that are part of the AMOC as well as of the subtropical cell (STC) of the Atlantic. These transports are manifest in the North Brazil Undercurrent (NBUC) and in the DWBC, which breaks up into deep eddies at around 8°S accomplishing the southward transport of deep water (Dengler et al., 2004).

Methodology. In order to measure these two western boundary currents at 11°S in the Tropical South Atlantic Array (TSAA), a mooring array is installed at the Brazilian shelf consisting of four full-depth moorings. Velocity within the upper 500 m depth is monitored with upward-looking ADCPs, while single-point current meters measure the velocity in deeper layers. Individual velocity observations are interpolated to a 12-hour resolution and low-pass filtered with a 10-day filter. The full field of alongshore velocity is then derived using a mapping scheme based on a Gaussian-weighted interpolation (Schott et al., 2005; Hummels et al., 2015). Transports for the NBUC and the DWBC are then integrated in predefined regions.

Results. More recent estimates of the transports at the western boundary at 11°S based on the reprocessed velocity time series (Hummels et al., 2015) yielded a mean southward transport for the DWBC of 17.5 ± 1.7 Sv and a northward transport of warm and intermediate waters within the NBUC of 26 ± 1.1 Sv (total average over the 2000–2004 and 2013–2014 time periods). The NBUC has a strong seasonal cycle (amplitude 2.5 Sv, maximum northward transport in July) while the DWBC variability is similar but out-of-phase (Schott et al., 2005). The DWBC additionally shows large variations at a 60–70 day timescale associated with the passage of deep eddies through the array.

To produce a basin-wide AMOC estimate, the eastern boundary current transport comprising primarily the Angola Current has been estimated using two ADCP moorings (SACUS/PREFACE) since July 2013. The full velocity field is obtained using a pattern regression analysis combining shipboard velocity sections and the ADCP time series (Kopte et al., 2017). Meridional Ekman transport is determined from satellite-based wind products. The deployment of two PIES at 300 m and 500 m at the western boundary at 11°S (July 2013) and complementary bottom pressure instruments at the continental slope off Angola at 11°S allows calculation of the upper-ocean interior transport variability across the Atlantic. Together these components will be used to produce a comprehensive AMOC estimate for the tropical South Atlantic.

1.4 Line W at 39°N (Western boundary array).

The Line W mooring array was deployed from May 2004 through April 2014, spanning the continental slope southeast of Cape Cod at 39°N (Toole et al., 2017). This array was comprised of six deep moorings from the 2238 to 4700 m isobaths (five moorings until 2008), producing daily estimates of the temperature, salinity and velocity, primarily below 500 m. Line W is situated beneath a satellite altimetry line, so that geostrophic velocity can be interpolated to the surface. Instrumentation included both fixed-point measurements (microCATs and current meters) and Moored Profilers, which sample in bursts that average over the tidal signal. The moored data were used to produce direct estimates of the DWBC transport in neutral density classes. Daily DWBC transport variability is large, ranging from nearly zero to more than 70 Sv of southward flow, with a mean of 22.8 ± 1.9 Sv. Comparing within similar density classes to other DWBC arrays, Toole et al. (2017) found that roughly 15 Sv are carried in the DWBC with recirculations augmenting transport significantly at 53°N, 26.5°N and 16°N. They also found that warm core rings and deep cyclones, spun up by the nearby Gulf Stream, cross Line W frequently and can bias the measured transport (Pena-Molino et al., 2011; Andres et al., 2016). From 2004 to 2014, there was a reduction in the total DWBC transport at Line W from 26.4 to 19.1 Sv, based on a linear fit to the daily transport estimates. By incorporating historical hydrographic data, Le Bras et al. (2017) found that water mass changes in deep LSW at Line W lagged changes in the Labrador Sea by about 5 years, which is consistent with measured DWBC velocities.

1.5 26.5°N PIES (Western boundary array)

PIES have been continuously deployed at 26.5°N in the Atlantic to capture the variability of the DWBC inshore of 72°W since September 2004. Barotropic transport variability between mooring pairs is calculated from pressure differences, while the baroclinic transport variability is estimated through thermal wind from the PIES-GEM-derived dynamic height profiles. Transport estimates over the April 2004 to April 2009 period shows that the DWBC transport variability is large (peak-to-peak range from -72 to +14 Sv) with a mean of 32 Sv. Note that this DWBC southward transport is larger (more southward) than the transbasin AMOC upper-limb estimate from RAPID for northward flow above 1100 m. Even when the deep flow is integrated all the way out to the MAR, it exhibits substantially more variability (standard deviation of 16 Sv) than the basin-wide AMOC (standard deviation of 5 Sv). The difference must be due to partial compensation of flows east of the MAR (Meinen et al., 2013a). The dominant (largest amplitude) variations of the DWBC at 26.5°N can be traced to Rossby Wave-like features propagating westward to the continental slope region from the interior (Meinen and Garzoli, 2014).

1.6 34.5°S PIES

An array of four PIES have been in place along 34.5°S between 51.5°W and 44.5°W since March 2009 to study the southward-flowing Brazil Current and DWBC. As with the observations at 26.5°N, the barotropic and baroclinic transports are estimated from pressure differences and PIES-GEM derived dynamic height differences, respectively. Two additional C-PIES were added by Brazil in December 2012 on the western boundary providing increased resolution of the DWBC as it flows southward along the continental slope. Variability at this latitude during 2009–2014 was high, with transports observed ranging from -89 Sv (southward) to +50 Sv (northward) within the DWBC layer in the array (Meinen et al., 2017). The observed standard deviation (23 Sv) is notably higher than has been observed further north. As with the observations at 26.5°N, the dominant sources of DWBC transport variability at 34.5°S appear to be westward propagating Rossby Wave-like features (Meinen et al., 2017). Additional moorings available on the eastern boundary during 2009–2010 and again since September 2013 have led to trans-basin AMOC estimates as the SAMBA line (e.g., Meinen et al., 2013b, 2018) and time series of eastern boundary water mass properties (Kersalé et al., 2018) and current transports.

1.7 Seasonal cycle of MOC at 34°S from climatology

Besides combining Argo and altimetry data, Dong et al. (2014) estimated MOC at 34°S on seasonal timescales using monthly climatologies of temperature and salinity from Argo data (above 2000 m), supplemented with the World Ocean Atlas 2013 below the Argo depth (below 2000 m). The authors found that the numerical models (NCAR CCSM4 and GFDL ESM2M) were unable to capture the strong seasonal variations in the geostrophic transport derived from observations. Dong et al. (2014) suggested that the weak seasonal cycle in the geostrophic transport derived by the models can primarily be attributed to strong stratification below the surface mixed layer, which inhibits the downward energy transfer.

1.8 XBT-based estimates of overturning at 35°S

The developments of those methodologies combining altimetry and Argo measurements to estimate AMOC, to some degree, rely on the AMOC derived from in situ measurements. In the South Atlantic, the longest AMOC and meridional heat transport time series from in situ measurements are from a trans-basin expendable bathythermograph (XBT) transect along approximately 35°S (namely AX18). The AX18 transect between Cape Town, South Africa and Buenos Aires, Argentina, providing the first critical time series observation in this region on quarterly basis since 2002. This quarterly time series has been used to validate the methodology developed by Dong et al. (2015). In the North Atlantic, a quarterly time series has also been provided by a trans-basin XBT transect along 26°N (namely AX07) since 1996, which will be used to validate a similar methodology as in Dong et al. (2015) to estimate AMOC and meridional heat transports in the North Atlantic from a combination of satellite sea level anomaly (SLA) and hydrographic data.

1.9 Oleander Project (Gulf Stream transport)

The Oleander project is a multi-decadal in situ observational program operated from the MV Oleander, a container vessel which sails on a weekly schedule between New Jersey and Bermuda. The project goal is to provide sustained measurements of ocean currents and temperature across four distinct regions: the continental shelf, slope sea, Gulf Stream, and northwestern Sargasso Sea. Of these, the Gulf Stream is a key component of the overturning circulation. Unlike moored observations, the ADCP-based measurements are high spatial resolution (horizontal and vertical), and unlike transbasin hydrographic sections, these sections are made weekly.

Key observational elements included high-horizontal resolution upper-ocean velocity measurements from a shipboard ADCP (since late 1992), monthly temperature sections using XBTs (since 1977), and surface salinity and temperature measurements from a thermosalinograph (since 2001). In the near future, platform improvements include a pair of ADCPs: a deep reaching 38 kHz instrument to measure across the main thermocline to ˜1200 m depth, and a 150 kHz instrument thus improving shelf-slope coverage. Observations of the Gulf Stream downstream of Cape Hatteras indicate that the near-surface transport, despite substantial interannual variations, shows no evidence as yet of a long-term trend (Rossby et al., 2014), nor does evidence exist for co-varying transport with the Florida Current (Sanchez-Franks et al., 2014).

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